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Photovoltaic techno-economical potential on roofs in regions and islands: The case of the Canary Islands. Methodological review and methodology proposal

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ABSTRACT

The literature review shows a wide range of methodologies aiming at determining the photovoltaic (PV) potential. Very often, the methodology scale is too large (continents, countries or large regions) or too small (cities) or it is based on specific and non-commonly available software tools. This is why the proposed methodology to determine the PV roof potential in regions and/or islands can be useful. This methodology has been applied to the Canary Islands. Firstly, the available roof area for PV systems is determined, based on the total roof surface (using real data from the Spanish Cadastre) and utilization factors according to the municipality type. The methodology proposed to calculate the available roof surface is then compared to other well-known methods, including potential improvements using Geographical Information Systems. Secondly, the mean annual global solar radiation per municipality on inclined surfaces has been determined. To do so, a review of different methodologies has been assessed in a comprehensible manner, seeking for the ones that provide accuracy and simplicity. Thirdly, the yearly PV production per municipality has been calculated. For this, a step-by-step method to calculate the PV system efficiency, based on existing literature, has been detailed. Three different scenarios depending on the shared use of the available roof surface are defined and the corresponding PV production is calculated. A sensitivity analysis is also included, analyzing PV production in two cases: depending on back ventilation of the roof-mounted PV systems and on PV cell type (poly-crystalline to mono-crystalline). Finally, an economic assessment based on cost-resource curves is carried out. The spirit of the paper is to develop a methodology based on accuracy and, at the same, simplicity, understanding such as a method where all the calculations can be easily done using pen and paper, calculator and common office software programs.

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1. Introduction

There is a double motivation that led to this research. On the one hand, the need to determine the building integrated photovoltaic (PV) potential in the Canary Islands and, on the other hand, the need to develop a methodology adapted to the regional/island scale that can be carried out utilizing commonly available software programs.

1.1. Methodological review

One of the most important aspects to be considered to determine the PV building potential is the size of the area to be studied. Very often the same techniques cannot be applied at local, regional or continental scale [1]. For instance, it may be possible to quantify the shadow effects among buildings of a city with a digital three-dimensional model [2] but this is not a practical option when the scope of the study is a whole continent. For similar reasons, homogeneous or average data are usually considered a first approach [3] for large-scale studies, which is obviously inaccurate but inexpensive indeed.

Several authors have developed different methodologies to determine the PV potential on roofs [1,4–21]. One of the key points to determine which methodology should be used is the scale of the study. For small regions or islands, the literature review does not provide accurate and inexpensive methods that could be applied obtaining reasonable results. Very often the scale considered in the articles is too large: continents [10,11,18,19], countries [1,12,20] or large regions [1,4,8,21]; or too small: cities [9] or urban areas [5–7,13–17]. This is why the methodology proposed within this study can be useful to estimate the PV potential on roofs in territories as small regions/islands.

Another important aspect to determine the method to be applied is the analysis of the data that are available. Therefore, scale and available data will determine which method can be used.

The main difference among the methodologies in the literature review concerns the method used to determine the roof area. Mainly three different types of methods could be identified.

1. Methodology based on the determination of the ratio roof surface per capita. The total roof area is calculated then by multiplying this ratio by the total population of the targeted area. The ratio is calculated examining a sample of the targeted area. These methodologies usually differ on how to determine and/or analyze the sample.
2. Methodology based on establishing a correlation between the population density and the roof area (a minor part of the articles reviewed uses this method).
3. Methodology based on computing the total roof area of the target region. There are some examples of this type of methodology in the literature review. However, this methodology is being increasingly used in the last years, particularly since GIS has become a common tool.

1.2. Regional considerations

The Canary Islands are seven islands belonging to Spain but located in front of the Western coast of Africa (parallel 28). This Archipelago is highly dependent on external energy sources; nearly 98% of the primary energy consumption is based on imported oil brought to the islands by ships. Speaking about electricity, this percentage reached the 94% [22] in 2010. The Canary Islands have no conventional energy sources, but they have plenty of renewable energy resources, mainly wind and solar.

For the Canary Islands it is really important to increase the level of energy self-sufficiency. This can only be reached through the deployment of renewable energy sources (RES). RES are

autochthonous energy sources that can contribute to reduce dependency from energy imports and to diversify the energy sources. In the same way, the deployment of RES can actively contribute to foster the employment and to encourage regional development. All these facts gain special importance in isolated regions like the Canary Islands.

The electrical power installed in the Canary Islands at the end of 2010 was 3049 MW, renewable energies came up to 8.4% of the total installed power but in terms of production this percentage represented the 6.2% [22]. The RES used in the Canary Islands are mainly wind and solar photovoltaic, 142 MW and 112 MW, respectively, in 2010 [22]. Most of the PV power is located in PV farms and only a minor part on buildings.

For the year 2015, the Canary Islands Energy Plan establishes that 30% of the electricity generation should be supplied by RES, mainly wind and solar. This plan establishes that wind energy has to reach 1025 MW, photovoltaic 160 MW and wave energy 50 MW [23].

However available land is scarce in the Archipelago. The total surface of the archipelago is 7447 km^2 and over 40% of this surface is protected. In 2011, there were around 2.2 million inhabitants on the islands and nearly 12 million visitors that year [24]. These numbers lead to an average population density of roughly 570 hab/km^2. Taking into account this context, it is understandable that land availability is an issue on the islands. There is a strong territorial pressure on the islands, finding available land for PV purposes is difficult since it competes with urban, rural and tourist developments and, when this is not the case, very often the natural environment wants to be preserved and, usually, no license is granted to build up PV farms.

Considering both issues, land scarcity and energy goals, it is crucial to determine the PV potential on roofs for each island as a first step for energy planning. Another advantage of building integrated PV systems is that it enables electricity production and demand at the same site, avoiding losses in the electricity distribution.

2. Methodology proposed: short description in three steps

The roof available potential is defined here as the part of the theoretical potential that can be harvested easily and in a sustainable manner, considering only the already constructed areas. This last means, taking into account the available areas on top of buildings, in urban and industrial areas.

The methodology used to calculate the PV potential follows three main steps:

1. Determination of the available roof area for PV purposes per municipality within each island/region (in this study the analysis is carried out at the municipality level firstly and the island level, secondly). This step represents the main novelty within the proposed methodology.
2. Determination of the annual mean global solar irradiation on optimally tilted plane, per municipality.
3. Determination of the yearly PV production per municipality (island and region) considering three case scenarios. The introduction of these three case scenarios represents also a novelty.

2.1. Available roof surface

The methodology to calculate the roof area usable for PV purposes follows the next steps:

1. Determination of the total roof area per municipality.
2. Classification of the constructed areas within each municipality as: residential, services and industrial.
3. Determination of the main buildings' types according to the regional architectural style and characterization of their roofs.
4. Determination of the utilization factor per building type.
5. Determination of the municipality type. Determination of the distribution of the building and roof types within each municipality type. Determination of the utilization factors for each type of municipality.
6. Calculation of the available roof area for PV purposes per municipality as a function of the utilization factors and the municipality type.

2.2. Mean global solar irradiation

The mean global solar irradiation on the horizontal plane, calculated as an annual average, per municipality is obtained from the radiation map of the Canary Islands developed by the Instituto Tecnológico de Canarias (ITC) —map available at: http://meteodata.itccanarias.org/—. For each municipality the mean global solar irradiation on a 23° tilted plane is calculated. One mean solar radiation value per municipality is selected, corresponding to the site with the highest population within each municipality, since this is the site where most of the roof surface is located.

2.3. Yearly PV production

The yearly PV production per municipality is calculated from the data obtained from the previous two steps, considering three different scenarios

1. The total available roof area is used for PV production.
2. The total usable roof area is utilized for energy production purposes: one part for solar thermal energy and the other part for PV production.
3. The roof area shares its surface between energy uses (both, solar thermal and PV) and other purposes not related to energy production (e.g. to hang out clothes).

The results show the total yearly potential PV roof production per municipality, considering the different case scenarios. The PV production is then calculated for each island and it is finally compared to the electricity demand.

3. Methodologies to determine the available roof area: review and proposal

3.1. Methodological considerations: review

The assessment of the PV potential on buildings usually starts with the determination of the total roof and façade areas. Once the total roof area for the targeted region is calculated, it is necessary to reduce this area to the one available for solar photovoltaic applications, in order to determine the potential power output. There are many factors influencing the fraction of available roof area, including: shading from other roof parts or from neighboring buildings and trees; use of roof space for other applications, such as ventilation, heating/air conditioning, stairwells or chimneys; and installation and tracking of PV panels themselves. This reduction in the available roof area is called by some authors "reduction coefficients" or simply "reduction" [1,8,20] while other authors call it utilization factor [10]; this last one is the denomination that is used within this study.

According to [10], the total roof area should be reduced according to its architectural and solar suitability. Whereas architectural suitability includes mainly limitations due to construction restrictions (HVAC installations, elevators, etc.), protected buildings (e.g. historical reasons) and shading effects, a.o., solar suitability takes into account the relative amount of solar irradiation that can be harvested on the surfaces depending on their orientation, inclination and the separation among PV panels. Solar-architectural suitability is expressed in relative terms and results in utilization factors [10]. Other authors do not distinguish between solar and architectural suitability, e.g. [1,4,8,20], considering all these limitations simply as different restriction coefficients. Within this study architectural and solar suitability are calculated individually.

The utilization factor, which is the result of the product of both solar and architectural suitability, determines the building PV potential in relative terms. In order to calculate absolute figures in square meters (m^2) and kilowatt-hours (kWh), the utilization factors have to be combined with building roof area and available solar irradiation [10].

Within this study only roof areas are considered because the efficiency of façade integrated PV systems is too low in comparison to roof mounted facilities, since the Canary Islands are located at a latitude of 28°, where vertical integration of PV systems leads to low profitability.

A literature review [1,4,10,15,20] provides different utilization factors that have been utilized by different authors. One novelty in this methodology is the use of different utilization factors depending on the building and municipality type, instead of using one single utilization factor for the whole study, e.g. [10], or different utilization factors depending only on the building type, e.g. [4,20]. The methodology utilized to calculate the usable roof area follows the steps mentioned in the previous section. These steps are described in the following lines. In the next section this methodology is compared to the methodologies found in the literature review.

3.2. Determination of the total roof area per municipality

For this study the smallest administrative division has been used, the municipality, to estimate roof areas and potentials. As a first step, the roof surface data have been processed from the database of the Spanish Land Registry—Spanish Cadastre—(data available at: http://www.sedecatastro.gob.es/). The data have been downloaded and classified per municipality and, for each municipality, the data of each property have been registered in a database. These data include wide information for each property, including some information that is not useful for the purpose of this study. A data mining process has been undertaken to extract the data needed per property, which are

- The class of property (urban, rural or special facilities): only the urban ones are of interest in this case.
- The roof surface of each property.
- The type of property: industrial, agro buildings, commercial, sanitary, educational, religious, spectacle, sports, offices, touristic and residential buildings.
- The type of construction.

Other data per property have been disregarded. The roof surface for each municipality has been calculated by adding the roof surface of each property within the municipality. These data have been utilized to calculate the roof surface per island. Table 1 shows the total roof surface per island, as well as for the whole Canarian region, in comparison to the island' surface.

3.3. Classification of the constructed areas per municipality

The constructed areas per municipality have been classified as: industrial, services and residential. For this purpose the buildings types have been clustered as follows:

- Industrial buildings: industrial and agro buildings.
- Services buildings: commercial, sanitary, educational, religious, spectacle, sports and offices buildings.
- Residential: touristic and residential buildings.

Some of the reviewed studies have only considered the residential areas [1], not taking into account the industrial ones. But, as it will be shown, the industrial areas have a large PV potential, and they have to be considered if the whole roof PV potential wants to be determined.

The residential areas have in turn been classified as: city, urban, tourist or rural; depending on the type of municipality. This classification is useful since, depending on the type of municipality, the architectural style and distribution differ substantially. The services areas (e.g. schools, hospital, commercial areas, etc.) and the industrial areas have mainly the same architectural style independently from the municipality type. But in the residential areas, the architectural style, and therefore the roof availability, depends on the municipality type.

For each municipality, the total surface has been classified per construction type. Table 2 shows the results of the total surface per construction type for the Canary Islands. These results show that the industrial and services areas account each one for nearly 20% of the total area, being the remaining 60% residential area.

3.4. Main building type and their roof characteristics

Building typologies in Spain are generally characterized by their compactness, compared to central and northern Europe [1]; this is also the case of the Canary Islands.

To identify the different roofs' types in the existing buildings in the Canary Islands, the building stock has been divided into five categories:

- Industrial buildings
- Services buildings (e.g. schools, hospital, commercial areas, etc.)
- High-rise apartment buildings
- Semi-detached and terraced houses
- Detached houses

The categorization within the Spanish Cadastre data includes nine different types of construction typologies, subdivided in 57 subcategories; which have been easily assimilated to the five

Table 1
Total roof surface per island and region.

	Gran Canaria	Lanzarote	Fuerte-ventura	Tenerife	La Palma	La Gomera	El Hierro	Total
Roof surface (km^2)	29.5	8.7	6.87	36.6	3.2	0.92	0.6	87.6
Island surface (km^2)	1560	846	1660	2034	708	370	269	7447
Percentage of roof vs island surface (%)	1.9	1	0.4	1.8	0.45	0.25	0.22	1.2

proposed categories. Moreover, the classification used for the residential building type within this study: detached houses, row or town houses and high-rise apartment buildings, is the same as the classification utilized by other authors as [4,7,20].

The lack of information on roofing types imposes the assumption of representative roofing typologies and its empirical analysis is based on visual inspection of Google Earth^{TM}, Google Map^{TM} images and a tacit knowledge of the region.

Industrial buildings: the industrial roof on the Canary Islands is typically a two-sided sloped roof, usually low inclined (around 10°, sometimes higher till maximum 22°) and, sometimes, even flat (0°). Understanding flat as roofs with no inclination (0°).
Services buildings: (e.g. schools, hospital, commercial areas, etc.): in the Canary Islands the services buildings' roofs are usually flat roofs.
Apartment buildings: the high-rise apartment buildings have mainly two types of roofs, flat roofs or mansard roofs.
Semi-detached and terraced houses: the semi-detached and terraced houses roofs are mainly flat roofs or pitched roofs (2 or 4 sides).
Detached houses: the detached houses' roofs are mainly flat or pitched roof (2 or 4 sides).

3.5. Utilization factors per building type

3.5.1. Architectural suitability factor

The architectural suitability leads to surface reductions mainly due three parameters: construction restrictions, protected buildings and shadow effects.

3.5.2. Solar suitability factor

The solar suitability factor depends basically on three parameters: orientation and slope of the roof and separation among PV panels.

3.5.3. Utilization factor: comparison to review literature

The global utilization factor is the product of both, architectural and solar suitability, resulting in the values shown in Table 8.

Table 2
Total surface per construction type in the Canary Islands.

	Industrial	Service	Residential	Total
Surface (km^2)	18.6	16.6	52.5	87.6
Percentage (%)	21.2	18.9	59.9	–

Table 3
Construction coefficients: literature review.

Building type	Construction coefficients [4]	[20]	[7]
Industrial	0.8	0.9	
High apartment houses			
Flat roof	0.8	0.7	0.654
Mansard roof			0.789
Townhouse or row			
Flat roof	0.9	0.7	0.796
Pitched roof			0.983
Detached house			
Flat roof	0.9	0.7	0.74
Pitched roof			0.974

These values can now be compared with the ones found in the literature review. Table 9 shows that the values within this study seem coherent but, for example, slightly lower than the ones proposed by [7] for residential areas, who calculated these coefficients for Andalusia (Spain). Since this study intends to be conservative, this result is considered appropriate.

Other studies do not include a classification like the one within this study but a simpler one distinguishing just flat and pitched roofs. Table 10 shows also slightly lower utilization factors within this study compared to the ones proposed by other authors. But, again, since this study intends to be conservative, this result is considered appropriate.

Construction restrictions due to elements located on the roof that make this surface unavailable for PV purposes, like HVAC installations, elevators shafts, air extractors, chimneys, antennas, stairwells, water tanks, etc.

Several authors have described this type of restrictions. Table 3 summarizes various authors' contributions that have been considered relevant for the purpose of this research. Other authors have utilized one single value for all buildings types, e.g. [10].

Table 4 shows elements that can be located on roofs as well as an assessment of their presence in different building types. There are some elements that are in common use in buildings in the Canary Islands, e.g. chimneys are not common in the Archipelago but some detached houses on the countryside have chimneys; however, since they are not common, they have not been included in Table 4. Some residential buildings, apartments or houses, have HVAC facilities, but most of the residential buildings do not have HVAC facilities, therefore they have not been considered either. Additionally, in the case of flat roofs, a perimeter space with a width of 1 m was considered necessary for maintenance work.

Taking into account different author's contributions and their territorial scope (e.g. it is not equally representative for our purpose a study developed in Vancouver than in Andalusia) as well as a visual inspection of some buildings through Google Earth^{TM} and Google Map^{TM} and the values in Table 4, the construction coefficients' values for this study have been calculated. Table 5 shows these values.

These values can now be compared with the ones in the literature review (see Table 3). It has to be noted that the values are similar to the ones proposed by the different authors, particularly by [7] for residential areas, who calculated the coefficients to obtain the useful roof surface, free of obstacles, in residential areas in Andalusia (Spain).

Protected buildings are those where, for any circumstance, no facility of any type can be built on. Usually most of the protected

Table 4
Roof elements & building types.

Building type	HVAC	Elevator	Air extractor	Stair-well	Antenna	Water tank
Industrial	–	–	–	X	–	–
Services	X	X	–	X	–	–
High apartment houses						
Flat roof	–	X	X	X	X	–
Mansard roof	–	X	X	X	X	–
Semidetached and terraced houses						
Flat roof	–	–	–	X	X	X
Pitched roof	–	–	–	–	X	–
Detached house						
Flat roof	–	–	–	X	X	X
Pitched roof	–	–	–	–	X	–

Table 5
Construction coefficients.

Building type	Construction coefficients
Industrial	0.95
Services	0.85
High apartment houses	
Flat roof	0.7
Mansard roof	0.7
Semidetached and terraced houses	
Flat roof	0.8
Pitched roof	0.9
Detached house	
Flat roof	0.8
Pitched roof	0.9

buildings are historical ones. This parameter strongly depends also on where the study takes place; in this sense it is not the same a study of the city of Vienna (which has numerous historical buildings) as one in the Canary Islands. This may explain the variety of values found in the literature review for this parameter while, on the other hand, some authors do not even take it into consideration.

For this study it has been considered, like other authors do [20], that among the industrial buildings no historical building will be found. The same consideration has been done for services buildings; therefore no reduction is foreseen for this type of building neither (note that in some place world-wide some services buildings are historical ones, but this is not usually the case in the Canary Islands). High-rise apartment buildings are seldom protected in the Canary Islands, anyhow, as a conservative approach, a coefficient of 95% is considered. For semidetached and detached houses a coefficient of 90% has been selected (other authors, like [20], used slightly higher coefficients for Sweden, of 90% and 85%).

The shading effect takes into account the effect of shadows generated by neighboring buildings, objects or by the roof configuration itself; it has to be taken into account that shadows move along the day and the season and, therefore, the affected area is not static and could be quite relevant. The range of values found in the literature review for this coefficient varies significantly (e.g. from 50% [1] to 10% shaded area [20] depending on building type and country). The shading effect has been carefully studied by some of the authors already mentioned. [1] have studied the influence of hourly shadows on monthly values via geometrical calculations with digital terrain models; their results show that the shadowing coefficient varies from 0.33 to 0.52 depending on the municipality type (as function of population and building densities) in Spain.

[7] calculated shadows cast by different construction elements (e.g. chimneys, elevator shafts, etc.) using AutoCAD software program. The percentage of solar radiation loss due to shading effect was obtained representing the obstacle profile on the roof and the sun band trajectory during the year (e.g. the percentage of solar radiation loss due to shadows for an elevator shaft located on a building roof in Andalusia—latitude 37—Spain, was 17.47% [7]). The criterion followed within that study was to eliminate all roof surfaces where solar shading radiation loss was bigger than 10%. The study concluded that the useful rooftop surface area, where a photovoltaic array could be mounted, was 82% of the total roof area.

In Phoenix, Arizona (latitude 33°) [6] utilized Google SketchUp for shadow analysis, a three-dimensional computer modeling program able to cast shadows based on the longitude and latitude of the site. The buffer area surrounding obstructions on the building rooftops were quantified based on selected equipment types in the case study area (that means that, if this method is applied to another geographical location, an assessment of the type of rooftop equipment found locally has to be done in order to select the appropriate buffer size that accurately reflects the effect of the shadow cast). Another uncertainty in shadow analysis is the orientation of obstructions on the rooftop. Different orientations may result in different sizes of shadow casts. The result of the study (which included 932 buildings) was that about 30% of the total rooftop area of unshaded predominately flat rooftops was suitable for PV applications.

All these three studies took place in sites (mean latitudes of 39°, 37° and 33°, respectively) that are comparable to some extend to the target region (latitude 28°), whereas the projected shadows in latitude 28° are shorter since the sun is more vertical. However, the values reported by the different studies differ substantially.

A shadow on a PV array will reduce the energy output, not only because of the loss of production where the shadow occurs, but also because this shadow reduces the production of the entire array [25]. One shaded cell in a module can decrease the energy output of that module up to 75% [26]. Therefore, if the capacity of one cell is compromised by a shadow, the production of the entire array will decrease. In this study, only unshaded PV systems are considered to minimize uncertainties associated with shaded PV cells and their reduced outputs.

In order to determine the shading coefficient within this study, different authors' coefficients as well as observations from cast shadows utilizing Google Earth™ have been taking into account. As this research aims to be conservative, the worst-case scenarios have been considered.

The shading coefficient strongly depends on the building type, but also on the municipality type, since the shadows projected on a detached house located in a city are different from the ones projected on another detached house located in a rural, disperse area. Moreover, also the local distribution influences the shading coefficient, the shadows projected on a detached house located in a city among buildings are different from the ones projected on one detached house located in a city within an neighborhood where all the houses are detached houses. Even more, a detached house in a rural-disperse area may or may not have tree shades. In short, this kind of shading influences should be taken into account in a local study, but the scope of this study (regional scale) makes it impossible to consider all these local factors and, therefore, the shading coefficients used are average ones depending on the building type and the most representative location for each building type.

Industrial buildings: industrial buildings have not been specifically assessed in the reviewed literature; and they are different from residential buildings. Industrial buildings are usually isolated, equally high and have fewer elements on their roofs than urban buildings. Therefore the shaded area is the smallest one of all building types considered. The shading coefficient selected is 5%, taking into account shadows projected only by elements located on the roof itself.

Services buildings: services' buildings are usually integrated in the cities. If services' buildings are surrounded by residential buildings, the higher buildings around them will project large shadows on them, since services buildings are usually not very high. On the other hand, big services areas are located usually far away from residential buildings, in isolated areas, and, therefore, neighboring buildings do not usually cast shadow on them. Services' buildings have usually more elements on their roofs than industrial buildings but bit less than residential buildings. Therefore, the shading coefficient for service buildings is higher

than the one for industrial buildings but lower than the one for residential buildings. The shaded area in big service areas is not big and it is estimated in 10%. However the shaded area in service buildings within residential areas is much higher, on the conservative side the highest coefficient calculated by [1] is assumed in this case: 52% (which correspond to high building density and medium population density areas). In order to calculate the average shading coefficient in service areas, the distribution of stand-alone service areas vs service areas integrated in town should be known. These data are not available but a rough estimation suggests a 50–50% distribution. Therefore, the shading coefficient for service areas is assimilated to 30%.

Apartment buildings: within the residential areas, shading coefficient depends on the building type. In the case of apartment buildings, higher buildings cast larger shadows. Since the territorial planning establishes the maximal number of stocks (and, therefore, the maximal building height) per town area, usually apartment buildings in the same area are equally high and shadows cast by neighboring buildings are not large. Apartment buildings are often located in the city and town centers. Therefore, the shading coefficient is considered the one calculated by [1] for crowded areas: 36% (areas with very high building and population densities).

Semidetached and terraced houses: as single and two-family houses are not as high as multifamily buildings, they are more exposed to shadow effects. Moreover, the shadow cast on their roofs is larger since higher buildings cast shadow on them. Therefore, the highest coefficient calculated by [1] is assumed in this case: 52% (which corresponds to areas of high building density and medium population density).

Detached houses: the shadows cast on detached houses are smaller than on semidetached/terraced houses, since they are to a great extend stand-alone buildings. Detached houses are more common in rural and disperse areas than in cities. However, one may find some detached houses also in cities and towns. The shading coefficient for this type of building is the one calculated by [1] for areas corresponding to low building density and medium population density: 34%

Table 6 shows the summary of the utilization factors for the architectural suitability. Note that the utilization factors are the complementary values of the reduction coefficients, e.g. if the shading coefficient is 5%, the corresponding shading utilization factor is 95%. The total utilization factor is the product of the three utilization factor components.

The roof slope is a parameter that typically depends on the building type. Considering that the optimal tilt angle of a PV system connected to the grid in the Canary Islands is 23°, the utilization factors per building type have to be determined.

Table 6
Architectural suitability: utilization factors.

Building type	Construction	Shading	Protected building	Total
Industrial	0.95	0.95	1	0.9
Services	0.85	0.7	1	0.6
Apartment houses				
Flat roof	0.7	0.64	0.95	0.43
Mansard roof	0.7	0.64	0.95	0.43
Semidetached/terraced houses				
Flat roof	0.8	0.48	0.9	0.35
Pitched roof	0.9	0.48	0.9	0.39
Detached house				
Flat roof	0.8	0.66	0.9	0.48
Pitched roof	0.9	0.66	0.9	0.53

Industrial: industrial roofs are typically two-sided sloped roofs, low-slope or flat. Usually, the whole roof surface is usable for PV purposes. Therefore, no utilization factor reduction is considered due to slope constrains, see [8]. In the case of flat roofs, it is possible to install panels over a tilted structure that covers the whole available roof area. The structure slope should be a bit higher than 20°. In this case, the PV available surface would be 1.063 times the roof surface (if "L" is the longitude of the roof, the longitude of the structure "*d*" will be: $d = L \cdot \cos 20° = L \cdot 1.063$). Anyhow, this increase in the available surface is not taken into account within this study. The orientation should either be a handicap. Since, however, it plays no role if the roof is flat and in low-slope roofs it should neither be a barrier to install PV panels. Therefore, the utilization factor for this parameter is one.

Services buildings: the services buildings' roofs are usually flat roofs. This case of flat roofs has already been analyzed in the previous paragraph and the same utilization factor of one is used.

Residential: the residential roofs in the Canary Islands are flat, mansard or pitched roofs (2 or 4 sides). The case of flat roofs has already been analyzed in the previous paragraph and the same utilization factor is used. In the case of mansard roofs in buildings, usually in the Canary Islands these roofs have two different slopes: the central part is low-slope roof (around 20°) and the edges are steep (around 45°). The edges will not be considered suitable for PV purposes, mainly due to its high slope, but also because part of this surface usually incorporates windows. The central part is the one suitable for the PV systems. The percentage of central vs edge surface changes from building to building. All in all, the central part is usually bigger than the edges. However, since this study intends to be conservative, the distribution is supposed to be 50–50%. Therefore, the utilization factor considered is 0.5. In case of pitched roofs (2 or 4 sides roofs), these roofs usually have a slope of 45°, which is too tilted for the 23° optimal tilt angles in this latitude. Therefore, this roof type is not considered suitable for PV purposes but they could be used for solar thermal facilities.

In regard to the orientation, as it has been already stated, in the case of flat buildings it plays no major role. In the case of mansard roofs as in pitched roofs, it is considered that they have 50% south-facing area on average [4,8]. This consideration leads to cut the available roof surface per building by half. In any case, this last plays no role for the pitched roofs since they have already been disregarded due to excessive slope.

Due to shading effects, the panels usually have to be separated from each other. The PV optimal slope in the Canary Islands is 23°. In buildings, PV panels are usually mounted directly on the roof with the same slope as the roof and, therefore, no distance between panels is foreseen. In the case of flat roofs, the PV panels could be installed on one single tilted structure that covers all the available roof area. The panels would be mounted on this structure in a similar manner as in a tilted roof casting no shadow on each other. If the panels were installed flat, the energy losses would be around 8%, therefore this configuration is also an option. In both cases, no distance among panels is required.

Table 7 shows a summary of the solar suitability utilization factors.

3.6. Determination of the municipality types and their utilization factor

The areas identified within this study are: industrial, services and residential. Industrial and service roofs are mainly flat or low tilted two-side sloped roofs (this last one only in some industrial buildings). The industrial and services roof areas can be accurately determined, since both areas can be calculated from Spanish Cadastre data. The industrial area results from the

addition of industrial and agro-buildings. The services area results from the addition of commercial, sanitary, educational, religious, spectacle, sports and office buildings.

The residential areas have been classified, depending on the municipality type, as: city, urban, rural or tourist. This classification constitutes a methodological novelty, since the literature reviewed does not establish any municipality classification, except for the one done by [1], who classified the municipalities depending on the building and population densities. Therefore, the classification and also its criteria are novel methodological inputs. These criteria are explained in the next lines.

To classify a municipality as tourist the criteria utilized is the total tourist area in comparison to the urban one: if the tourist area is bigger than 50% of the urban area, the municipality is considered tourist.

A municipality is considered rural depending, on one hand, on its architectonical configuration, disperse architectural distribution and predominance of one-family houses instead of apartment buildings, and, on the other hand, on population density. Rural municipalities are characterized by lower population density in comparison to urban ones. A population density of 200 persons/km^2 is one of the parameters used to distinguish rural from urban municipalities. This population density of 200 persons/km^2 has been determined taking into account the average population density of the Canary Islands, which is around 570 persons/km^2. The population density varies substantially depending on the municipality, registering data from 8 to 3731 persons/km^2. Therefore, the density 200 persons/km^2 corresponds to lowest population density areas, considered as rural. This value has been compared to the ones in the literature review [8] proposed to group the municipalities of Ontario (Canada) according to population density into three categories: low (up to 100 persons/km^2), medium (100–500 persons/km^2) and high (above 500 persons/km^2); the average population density of the considered area is 359 persons/km^2. The population density in the Canary Islands is around 1.6 times higher than the one in Ontario; the lowest population density considered for Ontario is 100 persons/km^2 and double (for rural areas) for the Canary Islands, which seems reasonable comparing the average corresponding population densities. Therefore, a combination of both, architectonical configuration and population density, have been considered to classify a municipality as rural or urban.

A fourth category has been included, referred to as city, for towns that have a higher compactness (higher percentage of high-rise apartment buildings) and population density than the so-called urban areas, which are also towns. In this case, the criteria selected for the city category are: population density higher than 1000 persons/km^2 and population density per roof area higher than 40,000 inhabitants per km^2 roof area (which is just as well as say that the roof area per capita should be 25 m^2 or lower). Wiginton et al. [8] considered the highest population density class above 500 persons/km^2. In this case the city class doubles that population density, which seems reasonable comparing the corresponding population densities (570 persons/km^2 in the Canary Islands vs 359 persons/km^2 in Ontario). The other criterion taken into account is the roof area per capita. The average ratio for the Canary Islands is 41.3 m^2 roof per capita. The selected ratio for cities is 25 m^2 per capita or smaller. This ratio speaks for the compactness and high density of high-rise apartment buildings as one of the main characteristics of a city.

The challenge now is to determine the percentage of each building type within each municipality type. The lack of literature references (since this part represents a novelty in comparison to other authors' proposals) and the lack of information on building typologies were solved utilizing the Spanish Cadastre data, where each property was associated to one construction typology. The different construction typologies have then been classified according to the building types considered in this study: industrial, services buildings, apartment buildings, semidetached or terraced-houses and detached houses.

A sample of municipalities, within each municipality type, has been selected to find representative values of building types

Table 7
Solar suitability: utilization factors.

Building type	Orientation	Slope	Total
Industrial	1	1	1
Services	1	1	1
Apartment houses			
Flat roof	1	1	1
Mansard roof	0.5	0.5	0.25
Semidetached/terraced houses			
Flat roof	1	1	1
Pitched roof	0.5	0	0
Detached house			
Flat roof	1	1	1
Pitched roof	0.5	0	0

Table 8
Utilization factors per building type.

Building type	Architectural suitability	Solar suitability	Utilization factor
Industrial	0.90	1	0.9
Services	0.6	1	0.6
Apartment houses	0.43	1	0.43
Flat roof			
Mansard roof	0.43	0.25	0.11
Semidetached/terraced houses	0.35	1	0.35
Flat roof			
Pitched roof	0.35	0	0
Detached house	0.48	1	0.48
Flat roof			
Pitched roof	0.53	0	0

Table 9
Utilization factors in residential areas: comparison to literature review.

Building type	UF	
	[7]	This study
High apartment houses		
Flat roof	0.52	0.43
Mansard roof	0.17	0.11
Semidetached/terraced houses		
Flat roof	0.54	0.35
Pitched roof	0.2	0
Detached house		
Flat roof	0.55	0.48
Pitched roof	0.21	0

Table 10
Utilization factors per building type.

Building type	Utilization factor			
	This study	[27]	[28]	[12]
Industrial	0.9	–	–	0.9
Services	0.6	–	–	0.9
Residential flat roofs	0.35 < UF < 0.48	0.65	0.6	0.5 < UF < 0.7
Residential pitched roofs	UF < 0.11	0.18	0.24	0.2

distribution for each municipality type. After processing the data, the results show the distribution of building types within the different municipality types, see Table 11.

The next step is to determine the roof type distribution within each building type, since each building type can adopt two different roof configurations. The roof types found in the residential areas are: flat, mansard and pitched roofs. The lack of literature references (since this part represents also a novelty) and the lack of information on roofing distribution imposed a review of regional articles [27,28], related thesis [29], statistical information [24] and an empirical analysis based on Google Earth™ and Google Map™ visual inspection. Table 12 shows the distribution of each roof type within each building type.

Table 11
Distribution of building types within each municipality type.

Municipality type	Apartment buildings (%)	Semidetached or terraced-houses (%)	Detached houses (%)
Urban	45	40	15
Tourist	40	45	15
Rural	20	30	50
City	60	30	10

Table 12
Distribution of roofs' types per building type.

Building type	Roof type	Distribution
High apartment houses	Flat roof	0.95
	Mansard roof	0.05
Semidetached/terraced-houses	Flat roof	0.7
	Pitched roof	0.3
Detached house	Flat roof	0.7
	Pitched roof	0.3

Finally, combining the buildings' utilization factors (Table 8), the buildings' distribution (Table 11) and roofs' distributions (Table 12) within each type of municipality, the utilization factor per municipality type can be calculated. The utilization factors for industrial and services areas do not depend on the municipality type but the residential ones do. Results of the utilization factors per municipality type are shown in Table 13.

The literature review do not provide a complete comparison to the values shown in Table 13 since this classification is broader than any other one found in the literature. But some authors provide utilization factors for some of the typologies, which may be very useful in terms of comparison. Loulas et al. [15] determined the utilization factor for specific urban areas consisting on squares of apartment blocks (flat roofs) in Thessalonica (Greece) using Google Sketchup and PVsyst software tools for the shading study. The utilization factor they obtained was around 0.4 (excluding solar thermal). This utilization factor is a bit higher than any of the utilization factors obtained within this study for residential areas. But, since this study intends to be on the conservative side, the utilization factors obtained are considered contrasted.

3.7. *Calculation of available roof area for PV purposes per municipality and island*

The available roof area A_a is the roof area that can be used for solar applications. This available roof area is computed from the total roof surface after applying the utilization factors shown in Table 12.

The available roof surface has been calculated for the 88 municipalities that constitute the Canarian Archipelago (34 municipalities in the province of Las Palmas and 54 municipalities in the province of Santa Cruz de Tenerife). Table 14 summarizes the available roof area per island and per surface type within each island.

Table 14 shows that the available industrial area (16.8 km^2) is even more important than the residential one (15.6 km^2), contributing to a relevant part of the potential PV production.

Table 13
Utilization factors per municipality type.

Type of municipality	Type of building	Roof type	Utilization factors per building & roof type	Building distribution (%)	Roof distri-bution (%)	Utilization factor
	Industrial	Flat	0.90	100	100	0.90
	Services	Flat	0.6	100	100	0.77
Urban	High apartment	Flat	0.43	45	95	0.33[a]
		Mansard	0.11		5	
	Semidetached/terraced-houses	Flat	0.35	40	70	
		Pitched	0		30	
	Detached house	Flat	0.48	15	70	
		Pitched	0		30	
Rural	High apartment	Flat	0.43	20	95	0.32
		Mansard	0.11		5	
	Semidetached/terraced-houses	Flat	0.35	30	70	
		Pitched	0		30	
	Detached house	Flat	0.48	50	70	
		Pitched	0		30	
Tourist	High apartment	Flat	0.43	40	95	0.32
		Mansard	0.11		5	
	Semidetached/terraced-houses	Flat	0.35	45	70	
		Pitched	0		30	
	Detached house	Flat	0.48	15	70	
		Pitched	0		30	
City	High apartment	Flat	0.43	60	95	0.35
		Mansard	0.11		5	
	Semidetached/terraced-houses	Flat	0.35	30	70	
		Pitched	0		30	
	Detached house	Flat	0.48	10	70	
		Pitched	0		30	

[a] $0.33 = 0.45\cdot(0.95\cdot0.43+0.05\cdot0.11)+0.4\cdot(0.7\cdot0.35)+0.15\cdot(0.7\cdot0.48)$ 0.33 = % apartment · (%flat roof · UF + %mansard · UF) + %terraced-house · %flat · UF + %detached · %flat · UF.

3.8. Case scenarios: available roof area

Within this study three different case scenarios have been taken into account, considering different available roof areas for PV purposes.

Scenario 1. total available roof area is dedicated to PV production.

Scenario 2. total available roof area is utilized for energy production, including one part for low temperature solar thermal energy (for hot water production) and another part for PV production. The surface needed for solar thermal energy has been calculated supposing that 4-m^2 solar thermal system is capable of providing hot water for one family house (average of 4 persons). In fact, the surface available for solar thermal systems is bigger since the whole surface of the pitched roofs and part of the mansard roof surface are also available for solar thermal systems (these areas were not considered suitable for PV purposes due to excessive slope). In any case, this additional surface has not been computed.

Scenario 3. available roof area shares its surface between energy uses (for both solar thermal and PV) and other purposes not related to energy production. The foreseen uses not related to energy are: to hang out clothes and some free-time space (sunbath, barbecue, etc.). The surface foreseen for this purpose is 1 m^2 per capita.

Table 15 shows the available roof area for PV production in the selected case scenarios. The results show that between Scenarios 1 and 2, the roof area diminishes 4.88% and between Scenarios 2 and 3, the reduction is 5.14%. The results show that, from a total roof surface of 87.6 km^2, the available roof surface for PV facilities (according to Scenario 1) is 43.4 km^2, a bit less than half of the roof surface. In the worst-case scenario (Scenario 3) the available roof surface is 39.1 km^2, representing nearly 45% of the roof area.

4. Methodologies review and intercomparison

The literature review addressing the determination of PV potential on roof is vast, e.g. [1,4–21]. The main differences among the methodologies reviewed are focused on

- Method to determine the roof area.
- Municipality classification and method to determine utilization factors within each municipality type.
- The introduction of different case scenarios.

4.1. Methodological review: determination of the roof area

The main difference among the methodologies found in the literature review [1,4–21], including the one within this study, is the method used to determine the roof area.

The major part of the literature review bases the roof area calculation on the determination of the ratio of roof surface per capita. The total roof area is then calculated by multiplying this ratio by the total population of the considered area. The effort in these methodologies is made on how to determine this ratio, which is calculated examining a sample of the targeted area. These methodologies usually differ on how to determine and/or analyze the sample.

A minor part of the literature review tries to establish a relationship between the population density and the roof area. And, finally, in some cases, the total roof area is computed.

4.1.1. Review of methodologies that use samples to extrapolate

Table 16 shows different ratios of roof surface per capita found in the literature review as well as the area covered by each study and the method utilized to determine the ratio.

Comparison to reviewed methodologies. The results of the study case have been compared with the results of the methodologies included in Table 16. It has to be highlighted that in this study case no accurate indicator of roof surface per capita has been found. The mean value for the Canary Islands is 44 m^2/hab but the mean deviation is 19; being the maximum value 128 m^2/hab and the minimum 18 m^2/hab. Therefore, no ratio can be established.

Methodology proposed by Izquierdo et al. [1]. Since Izquierdo et al. [1] implements a methodology that uses different ratios according to its municipality classification, a separate analysis is carried out in order to compare their methodology with the methodology proposed within this paper. Population and building densities are used to classify different municipality categories as follows: the population density is classified (from low to very high) as well as the building density (from low to very high), combining both densities to obtain each municipality category. Izquierdo et al. [1] has studied samples of each category and they have extrapolated the results for the whole Spain. For each category the available roof area per capita ratio and utilization factor are defined.

Comparison of results between both methodologies. Several municipalities fitting different categories of the classification made by Izquierdo et al. [1] have been selected. In order to

Table 14
Available roof surface per island and surface type.

Surface type	Available roof surface (1000 m^2)							
	Gran Canaria	Lanzarote	Fuerte-ventura	Tenerife	La Palma	La Gomera	El Hierro	Total
Industrial	5706	1153	1000	8088	615	154	68	16,784
Services	2913	790	598	4434	206	74	45	9062
Tourist	707	313	318	464	30	18	0.9	1851
Residential	5426	1690	1243	6279	689	186	144	15,656
Total	14,753	3946	3160	19,265	1540	453	258	43,374

Table 15
Available roof surface per scenario.

Scenario	Available roof surface (km^2)							
	Gran Canaria	Lanzarote	Fuerte-ventura	Tenerife	La Palma	La Gomera	El Hierro	Total
Scenario 1	14.8	3.9	3.2	19.3	1.5	0.45	0.26	43.4
Scenario 2	13.9	3.8	3.1	18.4	1.5	0.43	0.25	41.3
Scenario 3	13.1	3.7	3.0	17.5	1.4	0.41	0.24	39.1

determine the available roof area both methodologies, the one proposed by Izquierdo et al. [1] and the one proposed in this paper, were applied to the selected municipalities.

It has been found that differences in terms of roof surface were relatively high. The methodology proposed by Izquierdo et al. [1] resulted in roof surfaces nearly two times higher than the calculated ones for low-density municipalities. This difference was not so relevant in medium or high building density municipalities. Considering that the methodology proposed by Izquierdo et al. [1] does not take into account industrial buildings, this difference between roof areas is even bigger.

On the other hand, utilization factors utilized by Izquierdo et al. [1] are a bit lower than the ones proposed in this study. According to Izquierdo et al. [1], the total available roof area in the Canary Islands is 23 km^2 and according to the data processed within this study the available roof area in the Archipelago is 43.4 km^2 (as per Scenario 1). The results differ substantially, being the calculated available roof area nearly two times higher than the one calculated by Izquierdo et al. [1]. This can partially be explained due to the inclusion of industrial surface, which was not being considered by Izquierdo et al. [1].

4.1.2. Review of methodologies using population density to correlate

A number of researchers [8,19] have identified relationships between population density and roof area. Thus, it is important to investigate trends in both sparsely and densely populated areas of a region.

Lehmann and Peter [19] researched Northrine-Wesfalia (Germany), they claimed that they have found a relationship between the roof surface and the population density for the EU. They came to the conclusion that, in Spain, the average roof surface per capita was 13.5 m^2/cap. These values are far from the average values for the Canary Islands calculated within this study, with an average roof surface per capita of 41.4 m^2/cap.

Calculations done utilizing the correlation proposed by Lehmann and Peter [19] for a sample of municipalities in the Canary Islands show that this correlation does not match the roof surface calculated using the Spanish Cadastre data. Therefore, this method is indeed inexpensive but inaccurate for the studied region.

However, calculations show that there is a correlation between both parameters, population density and roof surface per capita, and, as other authors also stated, increasing population density leads to a decreasing ratio of roof area per capita [8,19].

[8,19] proposed to group the municipalities according to population density into three categories: low (up to 100 persons/km^2), medium (100–500 persons/km^2) and high (above 500 persons/km^2). They came to the conclusion that there is a constant linear relationship between population and roof area. This relationship was defined as: roof area (m^2)$=70\cdot$population$+237000$. This linear relationship had a correlation (R^2) of 0.993.

The data corresponding to the Canary Islands do not fit in the linear correlation proposed by [8,19], which is, on the other hand, logical, since the territorial distribution in Canada is very different from the one in the Canary Islands. However, this methodology poses the open question: can a linear relationship between population and roof surface be established in the Canary Islands?

Fig. 1 shows the relation between roof surface (km^2) and population in the Canary Islands. As it can be observed, there is a relationship between the two parameters, not a linear relationship but an exponential one.

[8,19] represented also the population density against the roof surface, obtaining a relationship that could be plotted as a third grade polynomial. However, [8,19] stated that the data processed were not sufficient to obtain a precise function to describe this complex relationship. In any case, the graph obtained does demonstrate the value in examining the relationship between population density and roof area per capita for small-scale analyses. Again, this methodology poses the open question: Can such a relationship between population density and roof surface also be established in the Canary Islands.

Fig. 2 shows the relation between roof surface (km^2) and population density in the Canary Islands. As it can be observed, no accurate relationship could be established between both parameters. In any case, the decrease of the roof surface per capita when the population density increases is confirmed, in line also with other authors' opinions [32].

4.1.3. Review of methodologies computing the total roof area

Up to day there are a few papers that have studied the whole targeted area [4,11,12,14,16,17,21]. However, this type of

Table 16
Literature review: ratio of roof surface per capita.

Literature reference	Ratio (m^2 roof/cap)	Ratio (m^2 available roof/capita)	Utilization factor (UF)	Area covered by the study	Method to determine the ratio	Comments
[10]	45	18	0.4	Central Western Europe	Statistical data & "rules of thumb" for solar architecture. Main assumption: typical value Western Europe, 45 m^2 ground floor area per capita	This study is referenced very often because it was among the first of its kind. This ratio has been used in, e.g.: [20,21]
		36		USA/ Australia		
		8		Japan		
[20]	74.4 (own calculations)	51	0.685	Sweden	Statistical data and estimations	
[8]	70 ± 6.2	13.3	Flat roof: 0.3 Pitched roof: 0.15	Ontario region (Canada)	Geographic information systems and object-specific image recognition applied to a sample	
[30]	17.6–21.2			Brazil		Rainwater catchment opportunities study
[31]	10.6–30.7			United Kingdom		Storm-water runoff study
[7]	32.3 (own calculations)		*Detached* Flat: 0.55; Pitched: 0.21 *Town house* Flat: 0.54; Pitched: 0.2 *High-rise apartment* Flat: 0.52; Pitched: 0.17	Andalusia	Data e.g. census. Determination of the mean surface per building type. Estimation of total number of buildings per type.	

methodology has increasingly being used lately. Especially since GIS has become a common software tool, given that GIS can be utilized to determine the roof area. The most relevant articles are described below.

Bergamasco and Asinari [4] studied the Piedmont Region (North-Western Italy), their objective was to assess the available roof area for PV facilities per municipality, as in the present research. The roof surface computation was not based on samples, but on the whole cartographic database of the region. Their methodology computes firstly all the roof area using Geographical Information Systems—GIS—by means of association of polygons. The entities (each entity corresponds to an object, such as buildings, roads, rivers, etc. and each polygon stores certain information, like its area and perimeter) have been filtered to calculate number of residential and industrial buildings per municipality and total available roof area. The results are represented as histograms of number of buildings and their corresponding roof surfaces, distinguishing residential from industrial buildings. The authors of the paper estimate a total error of 1.7% of the roof surface, which is, indeed, small.

Defaix et al. [11] estimated the potential for PV integrated in buildings in Europe. They developed a method using readily available statistical data on buildings from European databases. Therefore, they computed the whole roof area using European Statistics. To calculate the available roof area they applied a utilization factor of 0.4, as [10]; since they based their methodology on the one developed by Gutschner et al. [10].

Tereci et al. [14] used Light Detection And Ranging (LiDAR) data to build a local Digital Surface Model. Utilizing the GeoMedia Grid software program, they were able to classify the roof types in the targeted area (urban quarter Scharnhauser Park, Ostfildern, Germany) and identify roofs suitable for solar modules (flat or tilted roofs, south facing and not to steep). Then they determine the annual PV potential using an average annual global irradiation for the whole site.

Brito et al. [17] assessed the PV potential of a suburb in Lisbon, building a Digital Terrain Model and a Digital Surface Model from high-resolution LiDAR data and aerial digital photography. To calculate the solar radiation they used a GIS extension, which enables the mapping and analysis of solar irradiation over a geographic area for specific time periods.

Hofierka and Kaňuk [16] proposed a methodology for PV potential assessment in urban areas using open-source solar radiation tools including the r.sun solar radiation model (developed by Šúri et al. [33] and the web-based PVGIS estimation utility (developed by Šúri et al. [34] that can be effectively used for an on-site evaluation of PV installations. The urban area is represented by a 3-dimensional (3D) city model implemented in a GIS database. The applicability of the methodology is demonstrated using the example of a small city in eastern Slovakia.

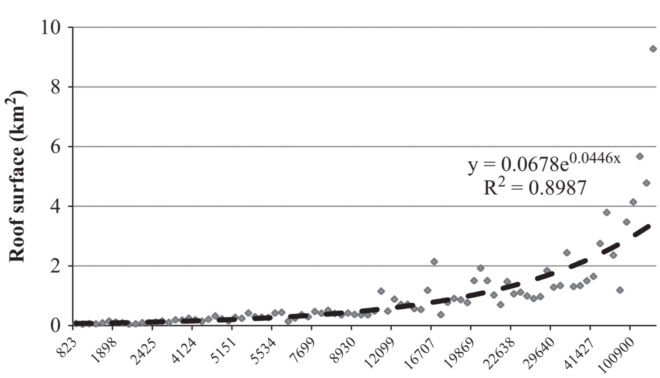

Fig. 1. Roof surface vs population.

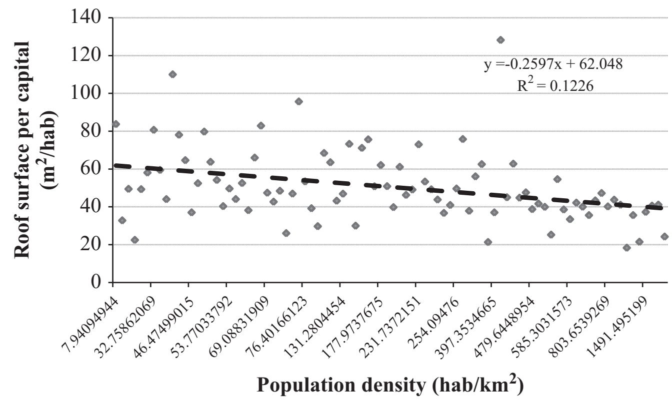

Fig. 2. Roof surface per capita vs population density.

Vardimon [12] used a GIS software and aerial orthophotos to calculate the total rooftop area in Israel. Orthophotos covering all towns in the country were analyzed by photogrammetric means to bound all buildings with polygons. The data set, consisting 1,200,000 buildings, covered all the country. Furthermore, all buildings were classified by purpose (commercial, industrial, etc.) according to governmental surveys. After obtaining the total roof area, different utilization factor per building type were used to calculate the available roof area.

The methods proposed by all these authors study accurately the whole targeted area usually using GIS; in any case, some error has always to be considered. However, it has to be highlighted that the computing effort to obtain these results is also considerable. These methods based on GIS are considered, therefore, to be accurate but intensive in terms of invested time and effort.

4.2. Methodology used in this study

The methodology proposed in this study is classified within this last group of methodologies, the ones computing all the targeted area. The methodology proposed to compute the roof area is, in principle, errorless since it computes the roof area of all buildings within each municipality. The data used are the ones from the Spanish Land Registry—Spanish Cadastre. The data are firstly classified by municipality and, for each municipality, the data of each property are registered. A data mining process is undertaken in order to extract the data needed per property, which are: property class, roof surface, type of property and type of construction. The roof surface per category within each municipality is then calculated.

The method should be errorless, however the possibility of some errors have always to be taken into account, which could come from errors in the Spanish Cadastre database itself or computing errors within this study.

In relation to the magnitude of time and computing effort, it is considerable but clearly smaller than in the case of implementing a GIS to calculate the total roof area. Additionally, this method is considered completely reliable.

The method proposed in this study is considered accurate, comparable in terms of accuracy to the ones proposed, for example, by [4,12,14,16,17]. However, the method proposed in this study is considered to imply less human and computing effort than the ones proposed by [4,12,14,16,17]. Additionally, in the present study, not only the roof surface per building type is computed but also the roof surface per construction type. From

the reviewed methodologies, the one proposed in this study is the only one that computes this parameter.

4.3. Methodology review: municipality type

The classification of the residential buildings within this study: detached houses, semidetached or terraced houses and high-rise apartment buildings, is the same as the one utilized by other authors [4,7,20].

Moreover, within this study, municipalities have been classified as: urban, rural, city and tourist, since the different nature of its main activity configures a different territorial distribution.

In the reviewed papers, the municipalities were not classified into different categories, except [1] who implemented a methodology that uses different ratios according to the municipality building and population densities. However, no accurate correlation has been found between the 17 categories proposed by Izquierdo et al. [1] and the four categories proposed within this study.

Therefore, this part of the study constitutes a novelty, not just due to the classification of the municipalities itself but mainly due to the utilization factors calculated for each municipality type. The motivation to do this classification was that the architectural distribution changes depending on the municipality type and, therefore, the utilization factors are different.

5. Global solar radiation: literature review

5.1. Solar radiation on inclined surfaces

The estimation of solar radiation on inclined surfaces is key for photovoltaic (PV) systems' calculations. However, measurements of solar radiation on inclined surfaces are very scarce. Usually tilted surface radiation is calculated from measured global horizontal radiation. These topics have been extensively covered by the literature, which offers a wide spectrum of models and correlations in order to estimate solar radiation on inclined surfaces [25,35–38]

Nevertheless, calculations using these models are not simple since information on direct or diffuse irradiance is required. This information can be determined using different methodologies. Related literature started in 1960, when Liu and Jordan attempted to describe solar radiation as a stochastic process [39].

5.2. Beam and diffuse components of the horizontal radiation from global radiation

[39] established a relationship between cloudiness index and diffuse fraction of the horizontal radiation.

Whereas the cloudiness index (K_{TM}) is defined as [39]

$$K_{\mathrm{Tm}} = G_{\mathrm{d,m}}(0)/B0_{\mathrm{d,m}}(0) \tag{1}$$

where

$G_{\mathrm{d,m}}(0)$: Daily global solar radiation (monthly average) on horizontal surface.

$B0_{\mathrm{d,m}}(0)$: Daily extra-terrestrial radiation (monthly average) on horizontal surface.

And the diffuse fraction of horizontal radiation (F_{Dm}) is defined as Ref. [39].

$$F_{\mathrm{Dm}} = D_{d,m}(0)/G_{d,m}(0) \tag{2}$$

where

$D_{\mathrm{d,m}}$ (0): Daily diffuse solar radiation (monthly average) on horizontal surface

K_{TM} and F_{Dm} are negatively correlated as clearer atmosphere implies higher global radiation and lower diffuse radiation. Liu and Jordan [39] established some correlations based on simultaneous measurements of both parameters at several sites.

Several authors have proposed different correlations. One of the most popular correlation is the one proposed by Page [40], who propounded a linear equation that usually leads to good results [25,36].

$$F_{\mathrm{Dm}} = 1 - 1.13 \cdot K_{\mathrm{Tm}} \tag{3}$$

There are other empirical correlations that establish the relation between both parameters for particular days, if correlations on a daily basis are considered necessary, see e.g. [41–44]. However, most of the practical PV calculations can be adequately solved using the monthly averages, therefore Eq. (3) is particularly recommendable [25,36].

5.3. Solar radiation on inclined surfaces from horizontal radiation

One way to estimate the global solar radiation on inclined surfaces (G(β, α)) is to calculate the three solar radiation components: beam (B(β, α)), diffuse (D(β, α)) and reflected or albedo (AL(β, α)) on an inclined surface. Consequently [25,36]

$$G(\beta,\alpha) = B(\beta,\alpha) + D(\beta,\alpha) + AL(\beta,\alpha) \tag{4}$$

where

β: inclination
α: azimuth (orientation)

5.3.1. Beam radiation

Beam radiation can be calculated as [25,36]

$$B(\beta,\alpha) = B(n)\max(0,\cos\theta_s) \tag{5}$$

where

$B(n)$: direct irradiance on a surface normal to solar rays. $\cos\theta_S$: can be calculated as a function of solar declination, site latitude, panel inclination and panel azimuth.

5.3.2. Diffuse radiation

The diffuse component of solar radiation is difficult to estimate and its calculation largely depends on the radiation behavior. The simplest method considers the solar radiance isotropic, which means that each point in the sky emits equally in intensity. Considering this model: [25,36]

$$\mathrm{D}(\beta,\alpha) = \mathrm{D}(0)(1 + \cos\beta)/2 \tag{6}$$

This method is, indeed, very simple but underestimates diffuse radiation on inclined surfaces [25,36].

Other methods consider all diffuse radiation circumsolar, which means that it all comes directly from the sun. These methods are also simple but overestimate the diffuse radiation on inclined surfaces [25,36].

Anisotropic methods lead to better results [25,36]. One of the most popular ones considers diffuse radiation a combination of isotropic and circumsolar components. Hay and Davies [38] proposed such a model, reaching an excellent compromise between accuracy and simplicity [25,36]. Their method has been broadly contrasted with experimental measurements all over the planet in the last decades [25,36]. Another method that is commonly used is the one proposed by [45], who considered the diffuse radiation as a combination of three components: isotropic, circumsolar and a third one from the horizon band. This method requires a previous estimation of direct and diffuse irradiance from the horizontal global irradiance. It has been

broadly used in computer calculations, being more complex than the previous ones.

5.3.3. Reflected or albedo radiation

Except for surfaces covered by snow, ground reflectivity is usually low. Therefore, the reflected or albedo radiation component over PV panels is usually low. This is why usually simple models are utilized to calculate the reflected radiation component, considering the ground a horizontal, infinite, isotropic surface [25,36]. Taking into account these considerations, the albedo component can be calculated as [25,36].

$$AL(\beta,\alpha)=\rho G(0)(1-\cos\beta)/2 \quad (7)$$

where

ρ: ground reflectivity, which depends on its composition. A common assumption is $\rho=0.2$ [25,36].

5.4. Determination of solar radiation on tilted surfaces

There are several methodologies to estimate the solar radiation on inclined surfaces from horizontal solar radiation. These methodologies differ in many aspects but, in line with the whole paper, two different aspects have been assessed: accuracy and simplicity, trying to reach a balance between both parameters.

5.4.1. Estimation of $G_{d,m}(\beta,\alpha)$ from $G_{d,m}(0)$

The most precise methodology to calculate $G_{d,m}(\beta, \alpha)$ from $G_{d,m}(0)$ can be described in three steps:

1. To calculate the hourly horizontal components: $G_{h,m}(0)$, $D_{h,m}(0)$, $B_{h,m}(0)$.
2. To calculate the corresponding hourly components on inclined surface: $G_{h,m}(\beta,\alpha)$, $D_{h,m}(\beta,\alpha)$, $B_{h,m}(\beta,\alpha)$ and $AL_{h,m}(\beta,\alpha)$, assimilating them to irradiance values.
3. To integrate these values throughout the day.

This method takes into account the anisotropic properties of diffuse radiation and leads to good results for any inclination (β) and orientation (α). However, its implementation is so complex that it requires the utilization of computers. That is why it was interesting to develop other methodologies that were simpler and easier to implement, even if there were not so precise [25,36].

5.4.2. Estimation of $G_d(\beta,0)$

Surfaces oriented to the Equator are the most common ones in PV applications. Therefore it is interesting to study this case, where the azimuth is cero, as a particular case of the previous one. Additionally, if one assumes the hypothesis of isotropy of diffuse radiation, the following expression can be applied: [25,36].

$$G_d(\beta,0)=B_d(0)RB+D_d(0)(1+\cos\beta)/2 \\ +\rho G_d(0)(1-\cos\beta)/2 \quad (8)$$

where

RB: relation between the daily beam irradiance (B_{0d}) on a tilted surface and on a horizontal surface [25,36].

$$RB=B_{0d}(\beta)/B_{0d}(0) \quad (9)$$

The RB factor can be calculated as a function of sunrise angle, solar declination, site latitude, panel inclination, panel azimuth and sunrise time.

5.4.3. Empirical correlations

The methods described in the previous two sections allow the calculation of solar radiation during any time period and on any surface (arbitrary inclination and orientation), when the starting data are the global horizontal radiation (monthly average). Nevertheless, these methods imply long calculation processes; therefore several software packages have been developed to perform these calculations [36].

However, the complexity of solar radiation models needed for most PV engineering calculations, like the yearly energy calculation, is low. Despite second order effects associated to wind, spectrum, etc., the energy produced by a PV grid connected system follows a quasi-linear relation. Time resolutions more accurate than hourly samples do not improve significantly the energy estimate. Moreover, the commonly available set of twelve monthly mean solar radiation data are enough to estimate the energy production, being the error lower than 3% [46].

Therefore, simpler methods can be developed to determine solar radiation on inclined surfaces. That is why several researchers have looked for correlations from empirical measured data, considering the simplest case of cero azimuth deviation ($\alpha=0$). [36] studied 46 sites along the world and established the following empirical correlation between daily solar radiation (annual average) on an arbitrary inclined surface ($G_{d,a}(\beta)$) and the optimally inclined one ($G_{d,a}(\beta_{opt})$) [36].

$$G_{d,a}(\beta)/G_{d,a}(\beta_{opt})=1+a(\beta-\beta_{opt})+b(\beta-\beta_{opt})^2 \quad (10)$$

where "a" and "b" are the coefficients of the correlation curve. The calculated values for both coefficients, obtained from the adjustment of the curve are

$a=4.46\times10^{-4}$
$b=-1.19\times10^{-4}$

Eq. (10) allows the calculation of the daily solar radiation (annual average) on optimally inclined surfaces ($G_{d,a}(\beta_{opt})$) from the daily horizontal solar radiation (annual average), which are the data that are usually available.

Other models have looked for similar correlations but for arbitrary oriented surfaces ($\alpha\neq0$); like for example [47], who proposed a correlation for arbitrary surfaces based on simulations done in Madrid and Paris.

5.5. Optimal tilt

The determination of the optimal PV tilt is key to obtain better performances from the system.

Many references can be found in the literature about optimal tilt for fixed PV generators. Some authors recommend a surface tilt equal to the local latitude [48–50]. On the other hand, some authors propose a tilt 20° below local latitude [51]. A very common value for grid-connected PV systems is a tilt 10° below local latitude [52].

However, there are physical reasons that suggest that the relation "$|\Phi|-\beta_{opt}$" is not constant, varying with the latitude (Φ). The difference between the hours of sun during wintertime and summertime increases with the latitude. Therefore, for higher latitudes the inclination of PV panels should point out more to the summer period than to the winter one in order to reach the optimum.

Lately, the tendency seems to be to develop empirical correlations from sites studies. Cronemberger et al. [53] studied optimal tilts in 78 cities in Brazil (latitudes between 0° and 30° South: 0° and −30°). They concluded that the closer is the location to the Equator, the higher is the inclination above the latitude. Indeed, from latitudes higher than 25°, the optimal tilt values are more likely the same of latitude's. This is due to the fact that, in low latitude areas, the maximum solar gain is obtained for slightly higher tilt angles than the latitude. It is precisely in locations with latitude higher than 25° when this tendency changes. They propose the following correlation between optimal tilt and latitude ($R^2=0.93$):[53].

$$\beta_{opt}=0.874|\Phi|+6.092^\circ \quad (11)$$

Lorenzo [36] analyzed 46 sites from the Arctic to the Antarctic (latitudes from 80° to −78°) in order to establish a relationship between optimal tilt and latitude, obtaining the following regression line [36]:

$$\beta_{opt} - |\Phi| = c + d|\Phi| \quad (12)$$

where "*c*" and "*d*" are coefficients whose values are

$c = 3.7°$
$d = -0.31$

5.6. Determination of solar radiation on tilted surfaces in the Canary Islands

Data available for the calculation of solar radiation on tilted surfaces are mean daily global horizontal solar radiation, annual and monthly averages, which can be obtained from the radiation map of the Canary Islands, developed by ITC (map available at: http://meteodata.itccanarias.org/). From these data, solar radiation on optimally tilted surfaces can be calculated using the methodologies described in the previous paragraph.

The first step would be to calculate the optimal inclination (β_{opt}). Using Eq. (12), latitude in the Canary Islands is 28°, β_{opt} should be 23°.

The next step is to calculate solar radiation on optimally tilted surface, which can easily be done using the empirical correlation proposed by Lorenzo [36]. Anyhow, solar radiation has been calculated using two of the three methodologies proposed in the previous paragraph in order to compare the results.

The first methodology determines the solar radiation on tilted surfaces calculating the three components of solar radiation on an hourly basis and integrates, afterward, these values throughout the day. This calculation has been done using the simulation software program IESPRO (a PV simulation software package developed by "Solar Energy Institute"—Polytechnic University of Madrid). The main parameters selected for this simulation have been: Erbs correlation [43] for the correlation between cloudiness index and diffuse fraction of horizontal radiation (daily and hourly correlation); the anisotropic model of Hay [38] for the determination of the diffuse radiation model; no spectral response was considered and the simulation period was 60 min. The results obtained were the following:

$$G_{d,a}(\beta_{opt})/G_{d,a}(0) = 1.0816$$

The third methodology in the previous paragraph uses an empirical correlation, Eq. (10), to calculate solar radiation on tilted surfaces. This calculation has been done using a basic calculator. The results obtained were the following:

$$G_{d,a}(\beta_{opt})/G_{d,a}(0) = 1.078 = 1.08$$

Therefore, the first and third methodology explained in the previous paragraph led practically to the same results, despite of being very different in terms of effort and complexity. This relation, $G_{d,a}(\beta_{opt})/G_{d,a}(0) = 1.08$, is the one being used to calculate the solar radiation on optimally tilted surfaces for all municipalities in the Canary Islands.

One mean horizontal solar radiation value for each municipality has been selected from the solar map. The selected values correspond to the town with the highest population within each municipality. From these mean horizontal solar radiation values, the global solar irradiation on a 23° inclined plane is calculated for all municipalities.

Table 17 shows the mean daily global solar radiation on the horizontal plane, annual average, $G_{d,a}(0)$, and the mean daily global solar irradiation, annual average, on a 23° inclined plane, $G_{d,a}(23)$, for a sample of municipalities, representing some of the settlements with the highest solar radiation and some with the lowest.

6. Yearly PV production: review, methodology and results

The total annual energy PV production is calculated as follows:

$$E = I_{md}\, 365\, e PR\, A_{PV} \quad (13)$$

where

I_{md}: mean daily global radiation on an inclined plane, calculated as an annual average
e: module efficiency
PR: performance ratio
A_{PV}: available area for PV production (after applying utilization factors)

The yearly PV production per municipality calculated using Eq. (13) shows the PV potential production in the case that all the available roof area were used for PV purposes.

6.1. PV system efficiency

6.1.1. Module efficiency

The energy output relies heavily on the type of photovoltaic modules used since variations in efficiency of more than a factor of two exist across materials and manufacturers [8].

Within this study, it has been decided to use commercial PV modules based on silicon. The efficiency of the modules is considered to be [54]: mono-crystalline $\eta_{MC} = 21.4\%$, poly-crystalline $\eta_{PC} = 17\%$ and thin film $\eta_{TF} = 8.2\%$. The modules utilized in this study are poly-crystalline ones.

6.1.2. Performance ratio

Several authors use different PV system efficiencies depending on the methodology utilized for its determination; e.g. some authors use a system efficiency of 80%—referred only to the system efficiency, not including the cell efficiency—[9]; other claim PV systems efficiencies between 10 and 20% [20] including, in this case, the cell efficiency.

The performance ratio or global system performance is defined as the relation between the annual energy effectively delivered to the grid and the one that would have been delivered by an ideal system (system without losses of any kind) under the same solar radiation conditions [36].

In order to determine the performance ratio, the system losses taken into account in this study are reviewed in the following lines.

Nominal PV power is calculated under the so-called standard test conditions—STC—(a.o. cell temperature of 25 °C). When the cell

Table 17
Solar irradiation in some municipalities.

Municipalities	$G_{d,a}(0)$ Wh/m^2 d	$G_{d,a}(23)$ Wh/m^2 d
La Aldea de San Nicolás	6050	6534
Pájara	5697	6153
Pozo Izquierdo	5615	6064
San Sebastián de La Gomera	5537	5980
El Cotillo	5529	5971
Vilaflor	5493	5932
/…/		
Arucas	4486	4845
Valverde	4420	4774
San Andres y Sauces	4339	4686
Barlovento	4338	4685
Hermigua	4337	4684

temperature increases over the reference one, the power output tends to decrease. The operating temperature is influenced by module design, mounting technique, irradiance level, ambient temperature, wind speed and, to a lesser degree, wind direction [55].

The losses due to cell temperature variations from the standard temperature are assumed to be 0.4%/°C [36]. The cell operation temperature varies as a function of ambient temperature and solar irradiation as follows [36]:

$$T_C = T_A + C_t G_{\text{ef}} \tag{14}$$

where:

T_C: cell temperature
T_A: ambient temperature
G_{ef}: solar irradiation (W/m^2)
C_t is a constant, calculated as [36]

$$C_t = (\text{NOCT}(^\circ\text{C}) - 20)/(800\ \text{W/m}^2) \tag{15}$$

where
NOCT: Nominal operation cell temperature

The NOCT usually varies between 42 and 47 °C [36]. However some experiments suggest that this value increases in roof-mounted cells, this temperature increase is around 17 °C if some back ventilation is allowed and could go up to 35 °C if panels are directly installed on well isolated roofs [56].

For the purpose of this study, the NOCT is estimated in 61 °C (44+17)—considering some back ventilation—therefore

$$C_t = 0.05\ ^\circ\text{C}/(\text{W m}^2)$$

and substituting in Eq. (14)

$$T_C = T_A + 0.05\ \ 800 = T_A + 40$$

In the Canary Islands the daily average temperatures range from 17 °C in winter to 23 °C in summer. Therefore, using Eq. (14), the cell operation temperature oscillates between mean values of 63 °C in summer and 57 °C in winter. The average cell temperature is 60 °C.

The lost due to temperature cell increase is estimated in 10%; resulting in η_{TH}=90%.

Another key factor to obtain the highest energy production from a photovoltaic panel is to maximize its exposure to sunlight. It is important to avoid shadows and expose the modules towards sun, mounting PV modules in the direction of the best azimuth angle (angle of the panel with respect to the south, 0°=South). The azimuth angle of fixed mounted integrated PV systems is usually the one of the longitudinal roof axis, which randomly differs from the best one (towards the south). To evaluate losses due to deviation of the azimuth angle, roof axes should be known. Territorial/cadastral data available do not provide orientation of buildings. In order to overcome this problem, a corrective coefficient has been introduced, assuming mean azimuthal deviation of 25° (which is higher than the mean expected deviation and would take into account facilities deviating from the South −50° to 50°, if they were uniformly distributed). Solar energy capture losses are estimated in 0.08% for each degree deviated from South direction [36]. Therefore, the mean azimuthal losses are 2% (η_{AZ}=0.98).

Angular and dirt effects originate a decrease in the PV output in comparison to the production at Standard Test Conditions (STC): normal incidence of solar radiation, reference spectrum and clean surface. PV modules performance is affected by the incidence angle of sunrays. Angular losses, caused by reflection and absorption in the materials covering PV modules (typically glass, encapsulate and antireflective coating), under non-normal incidence of solar radiation are significant in many practical situations. A complete analysis of these effects and calculations can be found in [57].

Some of the methodologies commonly used to calculate angular losses are, e.g., the one proposed by Ashrae [58], who calculated these losses, as a function of the incident angle. However, this methodology has the disadvantage that it does not take into account the losses due to dust effects, which are always present in real situations.

Lorenzo, Martin and Ruiz [36,59] proposed a formula depending on the incident angle and a parameter adjustable to the dirtiness degree. This method leads to good results but requires the calculation of solar radiance, which does not allow the utilization of the simplest methodologies to determine the solar radiation on tilted surfaces (Eqs. (8)–(10)) [36].

The combination of dirtiness and angular losses are relevant in most real cases. [36] studied these losses in several sites including different inclinations (β) and orientations (α) (β from 0° to 43.5° and α from 0° to 45°). Results showed that, in most cases, the losses due to dirt/dust and angular losses were between 7% and 10% [36].

A mean value of 8% has been considered for this study, therefore $\eta_{\text{D\&D}}$=0.92. In this sense it is relevant to mention that dirt and dust accumulate easier in flatter systems than in tilted ones.

Besides the above-mentioned losses, other secondary losses must be taken into account in grid-connected PV systems. Following losses have been studied.

Lorenzo [36] estimates losses of 0.2% due to floor reflection; within this study this loss is disregarded. They also estimate average inverter losses in 15%, although these losses can be reduced up to 5% in some cases. For this study, inverter loss is estimated in 10%, therefore η_{inv}=0.9.

Within this study the loss of efficiency due to degradation along the module lifetime is not considered. Another type of loss is the one related to the fact that PV generators do not usually match their nominal power. Therefore, it is more realistic to consider a PV generator power of 90% of its nominal power (η_{nom}=0.9) [60,56].

Taking into account all the above-mentioned efficiencies, their product leads to the performance ratio (PR).

The total PV system efficiency (η_{PV}) is defined as

$$\eta_{\text{PV}} = \eta_{\text{mod}} \cdot\cdot\cdot \text{PR} \tag{16}$$

$$\text{PR} = \eta_{\text{TH}} \cdot\cdot\cdot \eta_{\text{AZ}} \cdot\cdot\cdot \eta_{\text{D\&D}} \cdot\cdot\cdot \eta_{\text{nom}} \cdot\cdot\cdot \eta_{\text{inv}} \tag{17}$$

Substituting

$$\text{PR} = 0.9 \cdots 0.98 \cdots 0.92 \cdots 0.9 \cdots 0.9 = 0.66$$

This performance ratio (PR) value is in line with experimental results reported by [36], who concluded that experimental performance ratios lie in the range of: $0.65 \le \text{PR} \le 0.72$.

The PV modules chosen for this study are the poly-crystallines. Therefore substituting in Eq. (16)

$$\eta_{\text{PV}} = \eta_{\text{mod}} \cdots 0.66 = 0.112$$

6.2. Potential PV production in the Canary Islands

Table 18 shows the annual potential PV production (as per Eq. (13)) for a sample of municipalities, showing some municipalities with the highest potential PV production and some with the lowest one.

It should be highlighted that the municipalities with the highest potential PV production are not the ones with the highest solar radiation but with the highest available roof area.

Table 19 shows the potential PV production in the three considered case scenarios, in comparison to the electricity demand per island in 2010 and the potential PV coverage compared to the islands' electricity demand.

As Table 18 shows, the PV potential is very high, it could satisfy the whole electricity demand in all islands except for one, where it could meet 83% of the demand, in the worst-case scenario. Even if the roof surface were shared with other uses, PV could meet all the demand. Therefore, clearly it is worthy to foster PV roofs in the Canary Islands.

7. Sensitivity analysis

A sensitivity analysis is relevant to investigate the importance of design variables and its influence in energy production and, therefore, in generation cost. PV energy production depends on several technical factors, a.o.: cell type, installation characteristics, etc.

Two different factors have been analyzed in order to determine its influence in the energy output: the module type and the influence of back ventilation in roof-mounted panels.

7.1. Ventilation in roof-mounted panels

Fuentes and Fernandez [56] have researched the influence in the temperature of ventilation in roof-mounted panels. They concluded that the temperature increase over the NOCT is around 17 °C if some back ventilation is allowed and could go up to 35 °C if the panels are directly installed on a well isolated roof. The previous section showed the results of the energy production in the Canary Islands considering that some back ventilation was allowed and, therefore, the temperature increase over the NOCT was 17 °C.

In this section, the case of no back ventilation, panels directly installed on well-isolated roofs, is studied. The temperature increase over the NOCT is considered to be 35 °C [56]. Therefore, the NOCT is estimated in 79 °C (44+35). The average cell temperature is 78 °C (using Eq. (14)). The efficiency loss due to temperature cell increase is 20%; resulting in η_{TH}=80%. All remaining losses keep constant: same values as in the previous section. Therefore, the only parameter changing the value of the performance ratio (PR) is the loss of efficiency due to cell temperature increase, being the new performance ratio 58% (in comparison to the previous one that was 66%). This reduction up to 8% in the PR is just due to lack of back ventilation in roof-mounted system.

The energy production in the Canary Islands considering these panels with no back ventilation, for the three case scenarios considered also in the previous section, is shown in Table 20.

Table 20 shows that, even if PV potential is still very high, the energy reduction due to lack of back ventilation on roof-mounted panels is around 12−13%, and the electricity demand at regional level cannot be met. Looking at each island, 4 or 5 islands could meet the demand, depending on the scenario considered.

7.2. Type of module

The energy production showed in the previous section has been calculated using poly-crystalline-Si modules. However, the efficiency of the modules changes depending on the type of module considered. As per [54], the efficiency of the modules are: mono-crystalline η_{MC}=21.4%, poly-crystalline η_{PC}=17% and thin film η_{TF}=8.2%. Since the efficiency of mono-crystalline module is higher, one may wonder how the energy demand would be met if mono-crystalline modules were used instead of poly-crystalline ones.

For these calculations, the same performance ratio as in the previous section has been utilized (PR=0.66). The system efficiency increase due to the change from poly-crystalline to mono-crystalline is 2.9%.

Table 18
Annual PV production in a sample of municipalities.

Municipality	Usable roof surface (1000 m²)	Global Irradiation 23° tilted plane (Wh/m² d)	Yearly PV production (GWh/a)
Las Palmas de Gran Canaria	4938	5057	1023
S/C de La Laguna	2958	5424	657
S/C de Tenerife	2787	5317	607
Telde	2304	5371	483
Arona	1936	5482	469
S. B. de Tirajana	1652	5534	374
/…/			
Betancuria	25	5864	6
Puntagorda	26	5438	6
Artenara	25	5376	5.6
Garafia	27	5204	5.7
Tejeda	20	5234	4
Agulo	17	4821	3.4

Table 19
Annual islands' PV production in the three case scenarios.

Island	PV production (GWh/a)/ %			Electricity demand 2010 (GWh)
	Scenario 1	Scenario 2	Scenario 3	
Gran Canaria	3221/90	3129/88	2941/83	3560
Lanzarote	909/108	903/107	869/103	844
Fuerteventura	761/124	758/123	732/119	614
Tenerife	4342/123	4140/117	3938/112	3529
La Palma	330/131	312/124	293/116	252
La Gomera	101/142	96/135	91/128	71
El Hierro	54/133	52/127	50/121	41
Total	9719/109	9390/105	8914/100	8911

Table 21 shows the energy production using mono-crystalline modules in the Canary Islands, for the three case scenarios considered also in the previous section.

Table 21 shows that the energy production increase by changing from mono-crystalline to poly-crystalline cells is around 26–28%. In any of the 3 case scenarios, the regional and island electricity demand could be met by PV roofs.

Since mono-crystalline modules are more expensive than poly-crystalline ones, one could compare the production increase to the price increase and evaluate which type of module leads to higher profitability.

The literature review is scarce in regard to this kind of sensitivity analysis, with some exceptions. [13], for example, compared the performance of two different types of PV modules, but in this case they compared thin-film amorphous silicon (a-Si) PV panels and the more typical crystalline silicon (c-Si) panels.

8. Does GIS improve the results?

Within this study the yearly PV production has been calculated assuming a mean solar radiation value per municipality or area, as it is the case in other studies, e.g. [4,12,14]. In the consulted literature, PV production has mostly been calculated using average solar radiation values. Even if GIS was used, it was mostly used to calculate roof areas but not to compute solar production on concrete locations. Only few articles have used solar radiation data layer to compute the PV production on concrete sites, e.g. [16,17]. Although it is foreseeable that this tendency will increase in the near future due to the increasing

accessibility of GIS software programs and solar radiation data in GIS format.

Šúri et al. [61] suggest that GIS could contribute to the effective assessment of solar resources at supranational, national or regional levels. GIS offers an important tool for complex processing of spatial information. The interaction of solar radiation with natural and human environments requires the use of complex spatial database with relevant factors as well as GIS tools for processing spatial information.

One way to improve the data obtained within this study is to use a GIS to crosscheck roof surface data with solar map data (which includes solar radiation values in each cell). In this case, the roof area could be calculated in a similar way as it has been done by [4,12], another layer with solar map data has to be included and then both data, roof surface and solar radiation, have to be crosschecked for each grid cell.

In any case, the methodology to be selected depends on available data. The following cases can be found.

1. Accurate roof surfaces data (not geo-referenced) and solar radiation values: in this case no GIS system is needed in order to obtain roof surfaces since they are already available. If roof surfaces are not geo-referenced, a GIS cannot be applied. This is the case in this study.
2. No roof surface data and solar radiation values: in this case a GIS can be used to compute the roof surfaces. Since a solar map at grid cell level is not available, the solar radiation cannot be a layer of the GIS and the GIS cannot be used to calculate the PV production. This is the case in some studies (e.g. [4,12]).
3. Geo-referenced surfaces data and solar radiation values available (but no geo-referenced map): a GIS can be used to compute the roof surfaces but, since the solar map at grid cell level is not available, the GIS cannot be used to calculate the PV production.
4. Geo-referenced surfaces data and geo-referenced solar radiation map: a GIS can be used to obtain the roof surfaces and the solar map would be a layer of the GIS. Crosschecking both data, the PV production can be calculated. No paper of this kind has been found in the literature review.

This last method will not improve the roof surface data obtained in this paper but it will improve the PV production results since the solar radiation values of each cell are used instead one single average value for the whole municipality. This method is therefore, in principle, more accurate.

In this study, after observing the solar map data of the Canary Islands, it can be concluded that the solar radiation within one municipality tends not to vary much in average terms, deviating normally $\pm 5\%$ from the mean value, being usually the deviation is smaller. The implementation of GIS method, as explained in the previous paragraph, will lead, in principle, to more accurate results but also to a considerable higher personnel, time and computing effort. However, if the error computing the roof surface using GIS is bigger than 5%, the results could be even less accurate than the ones using the methodology proposed within this study.

Table 20
Annual potentail PV production: roof-mounted system without back ventilation.

Island	PV production (GWh/a)/%						Electricity demand 2010 (GWh)
	Scenario 1		Scenario 2		Scenario 3		
Gran Canaria	2831	80%	2750	77%	2584	73%	3560
Lanzarote	799	95%	794	94%	764	91%	844
Fuerteventura	669	109%	666	109%	644	105%	614
Tenerife	3815	108%	3638	103%	3460	98%	3529
La Palma	290	115%	274	109%	257	102%	252
La Gomera	91	128%	87	122%	82	115%	71
El Hierro	48	117%	46	112%	44	107%	41
Total	8544	96%	8254	93%	7836	88%	8911

Table 21
Annual potential PV production (mono-crystalline cells).

Island	PV production (GWh/a)/%						Electricity demand 2010 (GWh)
	Scenario 1		Scenario 2		Scenario 3		
Gran Canaria	4055	114%	3939	111%	3702	104%	3560
Lanzarote	1145	136%	1137	135%	1094	130%	844
Fuerteventura	958	156%	954	155%	922	150%	614
Tenerife	5466	155%	5211	148%	4957	140%	3529
La Palma	416	165%	392	156%	369	146%	252
La Gomera	121	171%	115	162%	109	154%	71
El Hierro	69	167%	66	160%	63	153%	41
Total	12,229	137%	11,815	133%	11,216	126%	8911

9. Solar PV cost-resource curves: review and case study

Cost-resource curves describe the amount of energy that can be provided by means of a particular technology option at a certain cost level [62]. The cost-resource curves obtained in this study are static cost-resource curves assuming current techno-economic parameters (2012).

The PV electricity generation costs are calculated for each municipality combining potential capacity and corresponding electricity generation costs. Electricity generation costs are calculated based on the economic parameters shown in Table 22.

The production cost of PV electricity (€/kWh) is calculated as

$$C_i = \frac{aI + Co\&M}{heg} \tag{18}$$

where

C_i: production cost of PV electricity (€/kWh)
a: annuity factor, given by $a = \frac{r}{1-(1+r)^{-LT}}$
I: investment cost (€/kW$_p$)
r: interest rate. In this case 6%. For this type of projects [64] suggested a value between 4% and 6% for the nominal discount rate and [63] a 5% for the Euro area and the USA (equivalent to an interest rate of 5.2%). The value of 6% has been set to be on the conservative side (note that this interest rate leads to higher productions' cost). Other authors use higher interest rates e.g. [18].
LT: lifetime (a)
$C_{O\&M}$: operation and maintenance cost (€/kW$_p \cdot$ a)
h_{eq}: annual equivalent hours (h/a)where annual equivalent hours are calculated as follows:

$$heg \frac{I_{md} e \text{ PR } rs{-}p}{1000} \tag{19}$$

where
I_{md}: mean daily global radiation on optimally inclined plane, annual average (Wh/m$^2 \cdot$ d)
e: module efficiency. In this case, polycrystalline silicon modules: $e = 0.17$
PR: performance ratio; calculated previously.
r_{s-p}: relation surface/power. In this case, $r_{s-p} = 7$ m^2/kW$_p$

The relation surface/power (r_{s-p}) has been obtained as an average value from the literature review [7,32,62,66].

The results of the static cost-resource curves are represented as a stepped function (see Figs. 3 and 4). Sites with similar economic characteristics (in case of solar PV, sites with same range of solar radiation) are represented by one band and, hence, a stepped curve emerges [62].

Fig. 3 shows the electricity generation costs of the PV systems that could be installed on the buildings' roofs in the Canary Islands. Fig. 4 shows also the same type of information but referred to installed power instead of electricity production.

Electricity demand in the Canary Islands in 2010 was nearly 9000 GWh. This last means that the PV marginal cost to meet this demand, according to Fig. 3, is around 12 c€/kWh; corresponding to an installed PV power of 6040 MW. The cost for this 6040 MW varies from 9 to 12 c€/kWh. The average electricity cost in 2011 in the Canary Islands was 20 c€/kWh [22]. In comparison to the current electricity prices, PV roofs seem to be competitive. In any case, the interpretation of these data should not be done literally. They represent the cost of PV roofs, but massive integration of PV systems in isolated/weak grids will lead to higher costs. First at all, each island should be analyzed individually, and the marginal cost for each island is different, since they are not interconnected (except for Lanzarote and Fuerteventura). And, secondly, since the electrical systems are isolated ones, storage systems, combination with other energy sources and grid reinforcements should also be considered. All these measures would enable a larger exploitation of the PV potential but increasing also the system costs.

10. Conclusions

Land scarcity, difficulties to obtain permits for PV farms and in situ production and demand are some of the reasons to foster PV roofs. The literature review shows different methodologies to determine the PV potential in buildings. One of the most important aspects to be considered to select the methodology is the size of the area to be studied since the same methods cannot be applied at local, regional or continental scale. Several authors have developed different methodologies applicable to different scales, but for small regions or islands the literature is scarce. This is why this paper proposes a methodology for this scale. The methodology to be used will also depend on the data that are available. Therefore, scale and available data determine which method can be used.

The main difference between the methodologies found in the literature review is the method used to determine the roof area. Mainly three different types of methods could be identified.

1. Methodology based on the determination of the ratio roof surface per capita. The total roof area is calculated by multiplying this ratio by the total population of the targeted area. The ratio is calculated examining a sample of the targeted area. These methodologies usually differ on how to determine and/or analyze the sample.
2. Methodology based on establishing a correlation between the population density and the roof area (a minor part of the literature review utilized this method).
3. Methodology based on computing the total roof area of the target region. There are some examples of this methodology in the literature review. This type of methodology is being increasingly used lately, particularly since GIS has become a commonly used tool.

From these methodologies, the most accurate one is the last one, since it studies the whole targeted area, but it is also the most arduous one. The first and the second methodology are less arduous but their results are also less accurate. For the Canary Islands, nor reliable roof surface per capita ratio could be found neither any accurate relationship between the population density and the roof area. If reliable ratios could be found, that would make calculations much easier, but it seems very difficult to find accurate ratios and, if any, they seem to be reliable only for very specific areas.

The methodology proposed in this paper falls into the third type of methodology explained. It allows an accurate and reliable estimation of roof PV potential when no geo-referenced data are available, but roof surface data and solar radiation data per

Table 22
Solar PV techno-economic parameters for cost-resource curve assessment.

Technology	Investment (I_0) (€/kW$_p$)	O&M costs (€/(kW$_p$ × a))	Life-time (a)
Roof-integrated PV plant Polycrystalline silicon	1800[a]	1% I_0[b]	25[c]

[a] This price is an average value from different commercial budgets of installed roof integrated PV plants based on polycrystalline silicon and from the Canarian Renewable Association (RICAM). Some literature references have also been consulted [18,32].

[b] [63,64].

[c] [18,47,63] Other authors use 30 years lifetime, e.g. [64,65], while other prefer to use 20 years [32,62] The value of 25 years is in between of those figures and, even more important, is the minimum considered production lifetime of a PV installation, which is usually considered to be 30 or 35 years.

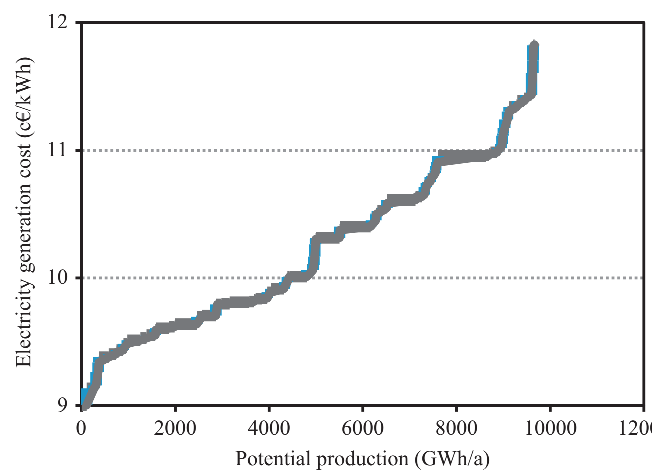

Fig. 3. PV electricity production cost.

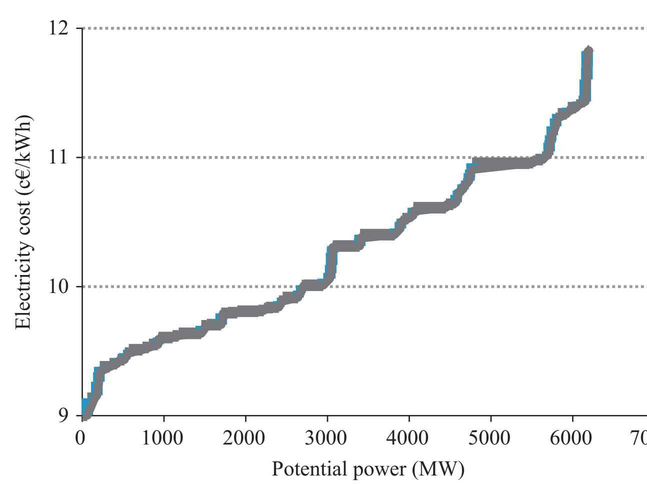

Fig. 4. PV power cost.

municipality are available. The methodology used to compute the roof PV potential should be selected according to the available data, e.g. if geo-referenced data are available the utilization of GIS is also a reliable option.

The main novelties within this paper are related to the methodology to calculate the available roof surface. Firstly, due to the determination of the roof area itself, no extrapolation or correlation methods were used, but the whole area was computed, using the Spanish Cadastre data. Most of the studies reviewed base their roof calculations on ratios. Within this study the roof area is determined using real data, which constitutes an added value for this kind of methodologies. It can also be concluded that no reliable correlation of roof surface per capita or between roof area and population density could be established.

Within this study, each municipality has been classified as urban, rural, city or tourist, since the different nature of its main activity configures a different architectural distribution. This classification led to the determination of different utilization factors according to the municipality type. This municipality classification constitutes also a novelty.

And last, but not least, three different case scenarios have been developed according to the utilization of the available roof area, taking into account a shared use of the surface for solar thermal and PV systems and also a combined use with other purposes (not related to energy production).

The results show the roof PV potential: from a total roof surface of 87.6 km^2, the available roof surface for PV facilities (according to Scenario 1) is 43.4 km^2, a bit less than half of the roof surface. In the worst-case scenario (Scenario 3), the available roof surface is 39.1 km^2, representing nearly 45% of the total roof area. This available roof surface seems to be enough, in regional average, to meet the electricity demand (2010) of the Canary Islands, nearly 9000 GWh, even if part of the available roof surface is used for solar thermal systems and some roof space is kept free for other purposes. Therefore, one of the conclusions that can be drawn is that, if the available roof area is used for PV purposes, a considerable part of the electricity demand could be met by solar energy. Theoretically, the potential PV roof production could meet the electricity demand, as regional average. But, in order to calculate how PV could meet the demand, calculations have to be done at island scale, showing that, for most of the islands, the potential PV production is higher than the electricity demand but not for all. The sensitivity analysis shows that variations on back ventilation of roof-mounted PV systems are very important, since lack of back ventilation could reduce PV production by nearly 13%. PV production is also very sensitive to cell efficiency variations: perceptual changes of 4.4% (from η_{cell} of 17%–21.4%) by changing the cell type (from poly-crystalline to mono-crystalline) may increase the PV production by more than 26%.

The economic assessment, based on cost-resources curves, shows how the PV cost varies when the installed power increases. To meet the electricity demand in the Canary Islands, 9000 GWh in 2010, the marginal cost of PV on roofs is 12 c€/kWh (the cost varies from 9 to 12 c€/kWh), which is still competitive in comparison to the current electricity cost of 20 c€/kWh in the Canary Islands. It must be pointed out that the PV calculated cost is a regional average and that this cost represents just the production cost of PV facilities but not the cost of massive integration of PV into weak electrical grids, which would be higher.

This paper provides an extensive review of the literature in this area. It provides also a powerful, but simple, tool to accurately estimate available roof surfaces for PV purposes as well as PV roof potential in islands/regions, providing also an estimation of its cost. All calculations can be easily done using pen & paper, calculator and office software applications, commonly available to everyone. Regions and islands trying to foster PV in their territories should benefit from this type of methodology to improve their energy planning.

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